Structural styles and Neogene petroleum system around the Yusuf-Habibas Ridge (Alboran Basin, Mediterranean Sea)

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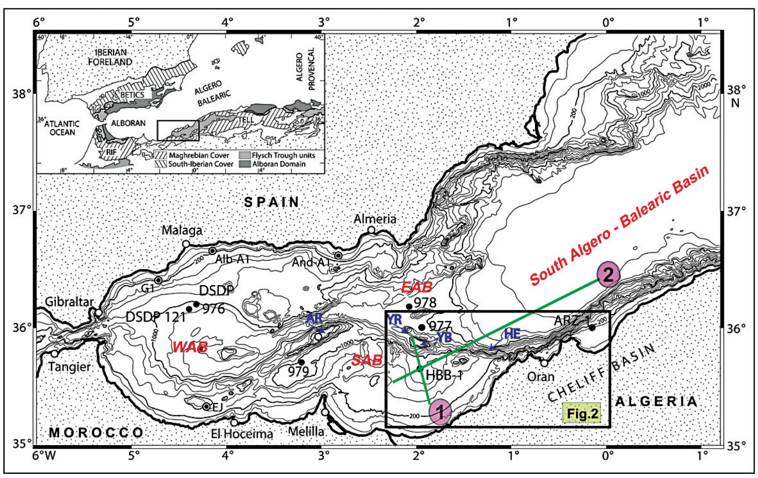
The Algerian offshore is part of the southern margin of the western Mediterranean Sea. The western part of this offshore area represents the transitional margin between the South Algero-Balearic Basin and the Alboran Basin. The study area includes the southern and eastern parts of the Alboran Basin and the northwestern part of the Algerian margin and is in the western part of the plate boundary between Eurasia and Africa (Figure 1).

The Yusuf-Habibas Ridge is a major EW-striking structure of this complex plate boundary, separating the eastern and southern parts of the Alboran Basin from the South Algero-Balearic Basin (Martinez-Garcia et al., 2011, and references therein). The ridge played an important role during the Neogene Alboran westward block migration between the Africa and Iberia plates, while the Kabylies blocks migrated southward and accreted to Africa. Furthermore, the ongoing NW-SE convergence between Africa and Iberia has induced a new stress field, since 7 Ma ago, replacing an earlier stress field (Fernandez-Ibañez et al., 2007) and leading to reactivation and polyphased deformation on the main structures in the basin, including the Yusuf-Habibas Ridge.

The aim of this paper is threefold: (1) to highlight the tectonic and structural styles of the Yusuf-Habibas Ridge; (2) to describe and correlate the stratigraphy of the South Alboran and Yusuf basins and, finally, (3) to discuss the elements of the Neogene petroleum systems has around it. To this end, we present and discuss new interpretations of various existing seismic reflection data to highlight the evolution of this ridge.



WAB= West Alboran basin,EAB= East Alboran basin, SAB= West Alboran basin.
AR= Alboran Ridge, YR= Yusuf Ridge, HE= Habibas Escarpment; YB= The Yusuf Basin
Comercial Wells= EJ, G1, Alb-1A, And-1, HBB-1 and ARZ-1, Deep Sea Drillig Programm: DSDP= 121, 976, 977, 978 and 979
1 and 2= Seismic cross sections used in this study.

***Figure 1.** Seismic cross section of the study area and tectonic sketch of the Alboran Basin. Modified after Comas et al. (1999).*

Exploration history

Along the western Algerian margin the water depth locally reaches a depth of 2500 m in the east but it becomes shallower westward (typical water depth between 1000 and 2000 m). The area has been the subject of numerous seismic, gravimetric/magnetic surveys, and drilling. The first seismic survey was conducted between 1968 and 1970, and the latest seismic data were acquired in the western offshore region by Sonatrach in 2002.

To date, the western Algerian offshore shelf and deep-water basin are still underexplored in terms of drilling, despite abundant and relatively good quality geophysical data. Only two wells have been drilled on the upper part of the margin (Figure 1). The first, relatively shallow well was drilled in Arzew Bay in 1974 (total depth of 1207 m). The second shelf well was drilled in 1977 near the Habibas Islands at the southern part of the Alboran Basin (total depth of 4496 m). This well has reached the Hercynian basement and proved the existence of a thick pre-Messinian Upper and Middle Miocene section. However, the well was a dry hole, most probably because of the lack of structural closure.

Bathymetric/morphological setting

The Alboran Basin is a sea about 400 km long and 200 km wide, with a maximum water depth of 2 km. It shows a complex bathymetric pattern (e.g., Comas et al., 1999) with several sub-basins, ridges and seamounts. The Alboran Ridge, in the central part of the Alboran Sea, is the largest. It forms a 180-km NE-SW linear structure and includes several volcanic edifices. The Yusuf-Habibas Ridge in the eastern part of the Alboran Sea is the second main bathymetric high of the region striking WNW-ESE. Due to these main ridges, three sub-basins were defined (Comas et al., 1999; Martinez-Garcia et al., 2011): the West Alboran Basin (WAB), the East Alboran Basin (EAB) and the South Alboran Basin (SAB).

The South-Alboran basin (SAB) is formed by a gently dipping northward plateau, lying between the Moroccan and Algerian coasts. The plateau is delimited to the north by a steep escarpment that is formed by the Yusuf-Habibas faults and forms a shelf margin with shoals (Banc of Câbliers, Provencal and Alidade) of volcanic origin. Eastward, the EW-trending Habibas escarpment limits the shallower (100 m) and very narrow (3000 m) platform of the Algerian margin from the South Balearic-Algerian dipping abyssal plain (2500 m). Between the East Alboran Basin and the Algero-South Balearic Basin, the transition is gradual and no escarpment is seen on seismic data.

The bathymetric map (Figure 2) is built from our data set by assuming a water velocity of 1520 m/s. The continental shelf bathymetry overall is very narrow except in the bays of Arzew (25 km) and Habibas (20 km). The steep continental slope is well defined between isobaths 200 m and 2300 m and it has an average width of 20–30 km. In the Habibas area, the continental margin gradually deepens.

Stratigraphy

The stratigraphy used in this work (Figure 3) was compiled from numerous onshore and offshore studies around the Betico-Rifan arc (e.g., Jurado and Comas, 1992; Comas et al., 1992, Chalouan et al., 1997; Fernandez et al., 1999; Cope, 2003; Booth-Rea et al., 2007; see also Soto et al. in this special section). Six seismic stratigraphic units labeled VI-I from base to top, tied to the commercial wells drilled offshore Spain, have been recognized within the seismic record of the basin (Jurado and Comas, 1992). According to these data and the internal Sonatrach biostratigraphy data of the Habibas well, we observe the following important points in our study area:

Seismic Unit VI. The oldest marine deposits overlying the basement beneath the Spanish and west Algerian margins are Aquitanian-Burdigalian in age, and consist of olistostromes with coarse clastics and shales.

Seismic Units V (Langhian) and IV (Serravallian/early Tortonian) consist of Middle to Upper Miocene sediments with undercompacted shales at the base passing upward into sandy and silty turbidites.

Seismic Unit III (Late Tortonian) includes sandstone intervals alternating with claystone and silty clay beds, as turbidite layers. Volcaniclastic levels intercalate throughout the middle and upper Miocene sequences.

Seismic Unit II (Messinian). These deposits have a shallow-water siliciclastic or carbonate facies, with occasional gypsum and anhydrite intervals. Unit II has a nearly uniform maximum thickness of about 250 m (or about 200 ms in TWT time) across the entire Alboran Sea Basin except in the Habibas Basin (HBB-1) where it is over 1000 m thick. However, large areas in the basin lack Messinian sediments, probably due either to erosion or no deposition (Figure 4). A well-developed Messinian evaporite sequence (i.e. thick salt) is notably absent, in contrast to the neighboring Mediterranean basins to the east (e.g., Ryan et al., 1973).

Seismic Unit I. The Pliocene-to-Pleistocene sediments penetrated by commercial wells consist mainly of fine-grained distal marls, clays, and scarce interbedded sandstones. The extensive diapir province in the West Alboran Basin involves sediments from Units VI and V and likely comprises undercompacted, overpressured material from these units (Pérez-Belzuz et al., 1997: Soto et al., this volume). The base of Pliocene– Pleistocene seismic Unit I, imaged in the seismic profiles as a prominent channeled, erosional unconformity, correlates with the top of the Messinian evaporite sequence recognized throughout the Mediterranean (i.e., the "M-reflector" of Ryan et al., 1973; Comas et al., 1999).

Based on the seismic facies units defined above, the sedimentary succession of the study area can be divided into two major sequences:

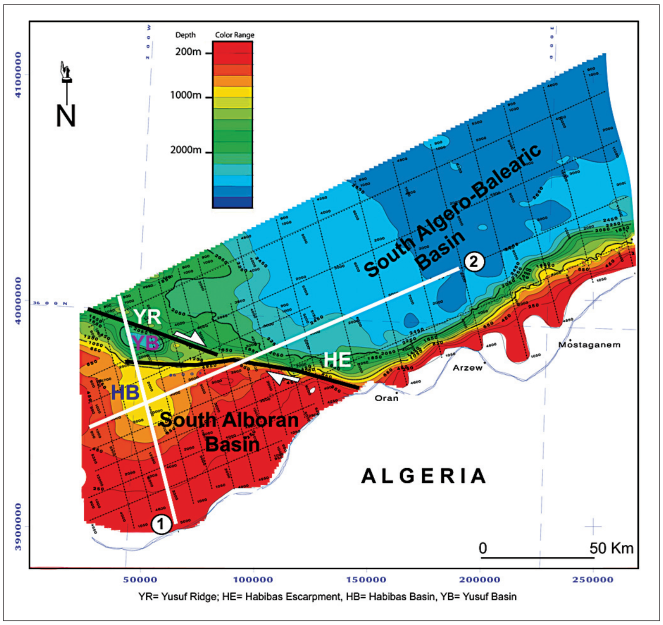


Figure 2. *Bathymetric map of the Algerian western margin showing the main structural features.*

1) The syn-rift sequence, Early Miocene-to-Lower Tortonian in age, coeval with the opening of the western Mediterranean basin. It has coarse clastics in some areas (Cheliff and Betics), whereas it is dominated by a clays in the offshore (e.g., Habibas Basin).
2) The post-rift sequence, extending from Upper Tortonian to Present, with the Messinian salt at its base followed by a succession of open-marine to deep-marine facies (clays, marls, turbidites). In the southern Alboran Basin, no salt deposit linked to the Messinian Salinity Crisis was noted due to the uplift of the Yusuf-Habibas ridge during the Tortonian NNE-SSW compressive event. The Pliocene lithology is mainly shales with a couple of sandstones within the beds above the Pliocene unconformity. These sediments are initially deposited in the bathyal regime, shallowing up into outer neritic at the end of the Pliocene.

The basement of the Alboran Sea beneath the syn-rift sequence consists of rocks similar to those found in the Rif-Betic Cordillera (Comas et al., 1992; Platt et al., 1998). Seismic and magnetic data indicate that the acoustic basement beneath the Alboran Sea is heterogeneous, formed of either metamorphic or volcanic rocks. Metamorphic rocks of the Betic and Rif belts have been recovered at the bottom of commercial wells offshore Spain and Algeria (sites HBB-1 and DSDP 121). East of 4° W, most bathymetric highs, sampled by dredging and diving (Mauffret et al., 1987), appear to consist of basaltic volcanics. Therefore the exact nature of the basement in the eastern Alboran region remains unknown.

In the onshore Cheliff Basin, Miocene-Quaternary deposits overlay a Mesozoic basement (Figure 5) formed by thrust sheets. However, the offshore distribution of this Mesozoic-deformed terrain is unknown. The base of the Cenozoic basin fill is represented by uppermost Burdigalian-to-Serravallian marls and sandstones. Overlying the latter, the Tortonian strata are made up of

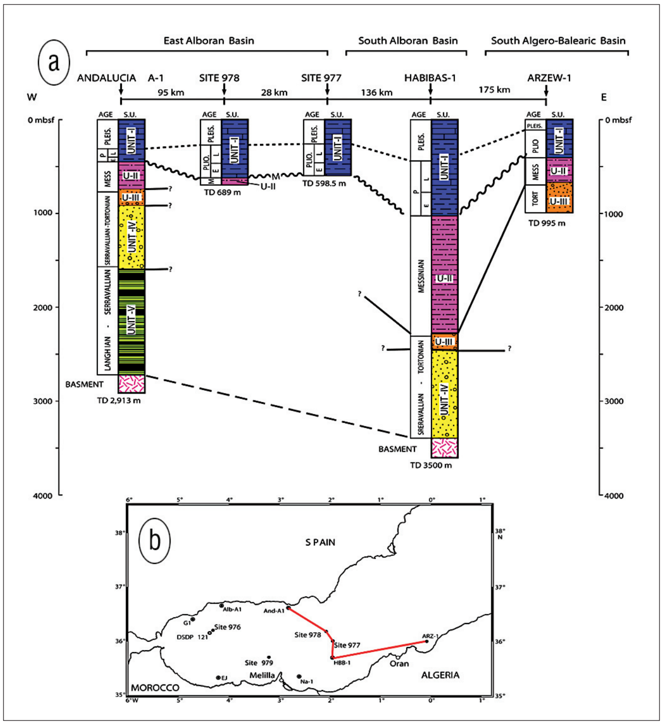


Figure 3. (a) Regional well correlation from Alboran Sea to the Algero-South Balearic Basin. Modified after Comas et al. (1999). (b) Location of well correlation profile.

limestones, marls, and sandstones. The Messinian sequence has marls alternating with diatomites and platform limestones. On top of the Messinian are massive gypsum beds with marl and sandstone intercalations.

The offshore Yusuf Basin on the eastern part of the Alboran Basin contains late Miocene-to-Plio-Quaternary sediments up to 2000 m thick (Figure 6), part of them having been drilled at ODP sites 977 and 978 (Alvarez-Marrón, 1999). In the deepest part of the South Alboran Basin, the Habibas area contains more than 4 km of sediments (Figure 7), which have been investigated by the deep-water Habibas well (e.g., Cope, 2003). Interestingly, no significant Messinian evaporites were found in this well and no hiatus have been identified at the end of the Messinian period. Based on the seismic data (Figure 6), the unconformity marking the end of the Messinian is characterized by erosive scars. The Pliocene sequence represents a renewed deepening of the basin with sediment deposited initially in the bathyal regime shallowing up into outer neritic at the end. The dominant lithologies are shales with some sandstone layers (shingled turbidites?) within the package sitting on the Pliocene unconformity.

The western part of the South Algero-Balearic Basin has a thick section of sediments deposited at the base of the continental slope. The shelf area of the Algerian-South Balearic margin was penetrated by the Arzew well (Figure 1) drilled on a seismically defined Miocene–Pliocene structural nose (Burollet et al., 1978). In contrast to the Habibas well, in the Arzew well a massive, 129 m thick Messinian gypsum bed has been found.

Structural styles

The Neogene history of the Alboran Basin and the western part of the South Algero-Balearic Basin is closely related to the geological history of the Alboran block and its collision with the Betic and Rif chains. Two main opening periods can be detected on seismic sections. The first one is Aquitanian-to-Burdigalian in age and is related to the NNW-SSE opening of the Valencia Trough. This extension is attested only by the geometry and the thickness variation of the sediments with no clear evidence for the existence of syn-rift tilted blocks. The second Langhian-to-Tortonian extensional period is roughly contemporaneous with the westward migration of the Alboran block and its collision (at ca. 10 Ma) with the Betic and Rif domains. This extension is well identified in the South Balearic-Algerian Basin where westward-tilted blocks and associated growth strata were well defined in the seismic cross sections (Figure 7). In the South Alboran Basin (Habibas Basin), the Langhian-to-Messinian deposits show onlapping geometries: they have filled the depressions induced by the fold-propagation faults to the south and southwest (Figure 6). These thrust faults are well recognized onshore (e.g., Yelles-Chaouche et al., 2006), and well expressed in the piggy-back basins such as in the Cheliff Basin (Bracene et al., 1998).

As illustrated by seismic cross sections (Figures 6 and 7), the Pliocene unconformity marks a major tectonic event in this part of the western Mediterranean. In fact, the latest Tortonian compressional episode might be responsible for the water drawdown in the Mediterranean. The NNW-SSE main stress reorientation implies an eastward motion of Africa relative to Europe which also generates a dextral transtension along the EW-striking faults (Martinez-Garcia et al., 2011) and it started the opening of a Plio-Quaternary pull-apart basin (Yusuf Basin).

At present, the Yusuf-Habibas Ridge constitutes a major morphological limit at the western end of the southern Algerian-Balearic Basin. It is limited to the north by a large fault system that is among the longest structures along the complex plate boundary between Eurasia and Africa and is potentially absorbing an important part of the present-day deformation (Martinez-Garcia et al., 2011).

From sea-floor morphology, the Yusuf-Habibas fault zone shows different segments with lateral tips in relay, accommodated by en-échelon folds, suggesting transtensive deformation. The Yusuf Basin has a rhomboid-shaped bathymetric expression, bounded to the north by the steep Yusuf Ridge and to the south by the less steep African continental slope. Mauffret et al. (1992) interpreted the Yusuf Basin as a present-day pull-apart basin (or negative flower structure) developed next to the Yusuf strike-slip fault. In contrast, the adjacent Yusuf Ridge (900 m high relative to its surroundings) has been interpreted as a push-up block (or positive flower structure).

Within the Yusuf-Habibas Ridge, seismicity is scarce, occurring partially along the main faults (Martinez-Garcia et al., 2011). However, some low-magnitude earthquakes (Mw <3) in the Yusuf Basin clearly show that some of the bounding faults are active today. The single focal seismic mechanism affecting the Yusuf Ridge reveals right-lateral, transtensive deformation, for faults trending NW–SE. This observation is consistent with normal displacements observed along active faults seen in this zone from high-resolution seismic sections. These observations support previous interpretations (e.g., Alvarez Marrón 1999; Comas

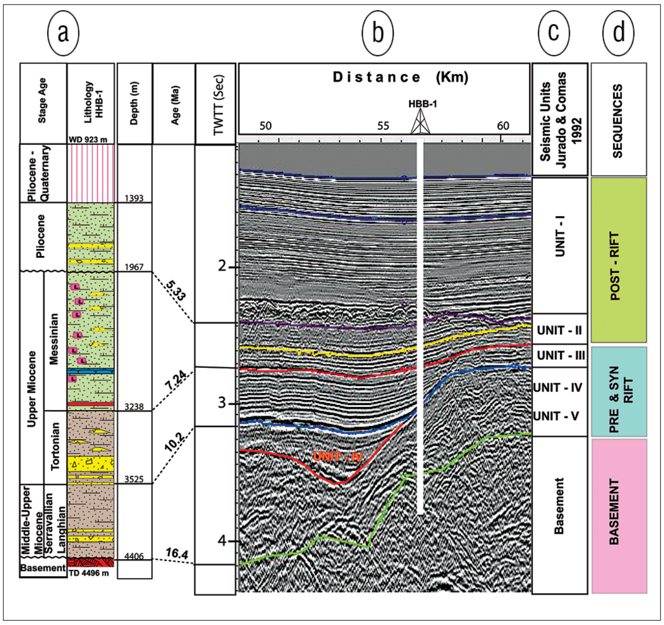


Figure 4. Seismo-stratigraphic chart of the Algerian South Alboran margin.

et al. 1999; Fernández-Ibáñez et al., 2007; Martinez-Garcia et al., 2011) of the Yusuf-Habibas ridge as a fault structure with right-lateral, transtensive deformation.

Other right lateral strike-slip faults parallel to the Yusuf fault have been interpreted to occur at bathymetric breaks along the southern side of the basin (Habibas Escarpment). Two oblique topographic breaks may correspond to synthetic faults between the areas of right-lateral strike-slip systems. Post-Messinian deformation along these faults effected even the Pliocene-Holocene sedimentary sequences. However, folding and strike-slip faulting seem to have already started in the Late Miocene (Martinez-Garcia et al., 2011).

Petroleum systems

Apart from the two boreholes (HBB-1 and ARZ-1) drilled on the shelf in a foreland basin setting, no exploration drilling has been done in back-arc basins. This translates to significant uncertainties regarding the petroleum system elements (source, reservoir, seal and structure) in this part of the Algerian offshore.

Reservoirs and seals. Three main reservoirs are recognized in the Habibas well sedimentary section: (1) sandstones in the Pliocene, above the Messinian evaporites; (2) sandstones in the Middle-to-Upper Miocene, below the Messinian evaporites; and (3) carbonates and sandstones in the older allochthonous units.

In addition to these reservoir sands, an interval with chaotic patterns (MMCR) is seen on seismic and HBB-1 well data (Figure 6). Unfortunately, at the well location, this interval is very thin; therefore the exact nature of this lithologic unit remains to be seen. However, in an internal Sonatrach sequence stratigraphic and biostratigraphic study, it was interpreted as a slump or as a carbonate ramp with mounded buildup. If it is a carbonate platform, it could have porosity with favorable reservoir properties.

Neogene sandstones are considered to be the primary target in the offshore area with stacked units of thickness 20–100 m.

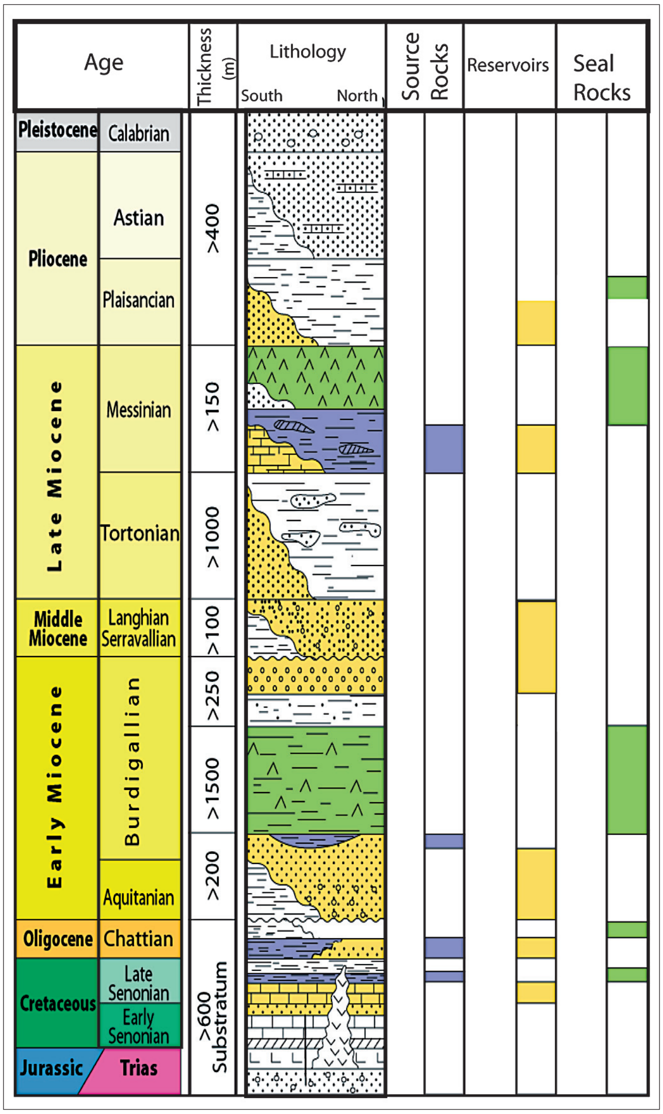


Figure 5. Generalized stratigraphic chart of the onshore Cheliff Basin and its petroleum systems as an exploration analog for the offshore area.

The porosity range is typically 4–18%. However, deep-water marine sandstones also occur in the Pliocene of well HBB-1 as stacked units with thickness of 5–20 m displaying excellent porosity character in the range 20–26%. In the Cheliff Basin (Ain Zeft and Tliouanet fields), production has been possible from Upper Miocene (Tortonian) marine sandstones (Figure 5). Similar sandstones are recognized in the Upper to Middle Miocene (Tortonian-Serravalian) of well Habibas-1.

The Messinian evaporite sequence acts as an efficient regional top seal. Within the Miocene, reservoir units can be locally sealed by interbedded shales. Seals for older reservoir formations are assumed to be locally developed interbedded shales or tight carbonates. A regional seal top formed by shales is expected immediately above the base Miocene unconformity.

Source rocks, maturation, and hydrocarbon migration. Several source rocks are known regionally from Miocene, Paleogene and Cretaceous times. In the Cheliff Basin, the Upper Miocene Tripoli marls are oil-prone source rocks with up to 3% total

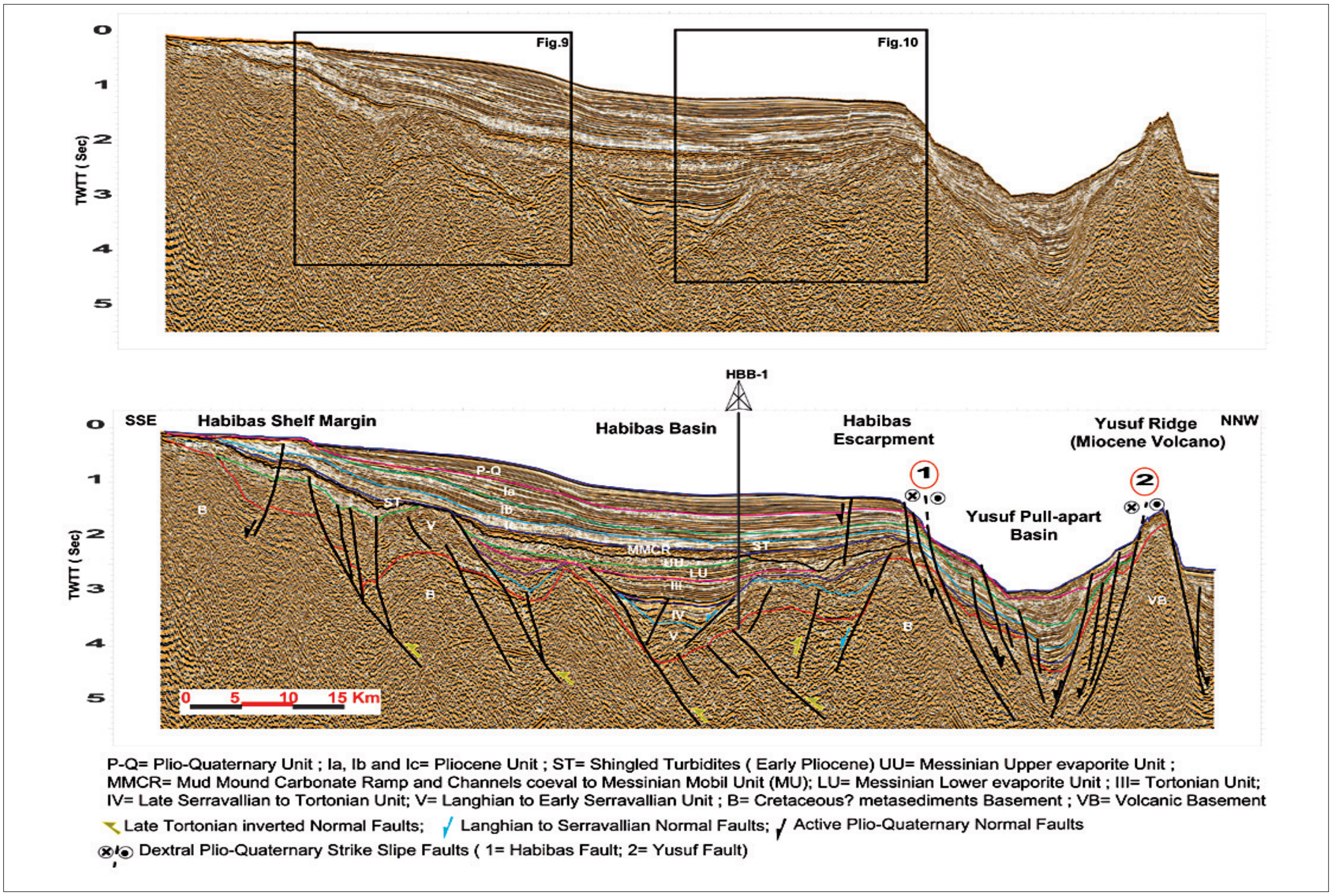


Figure 6. *Seismic cross section from the South Alboran margin to the East Alboran Basin.*

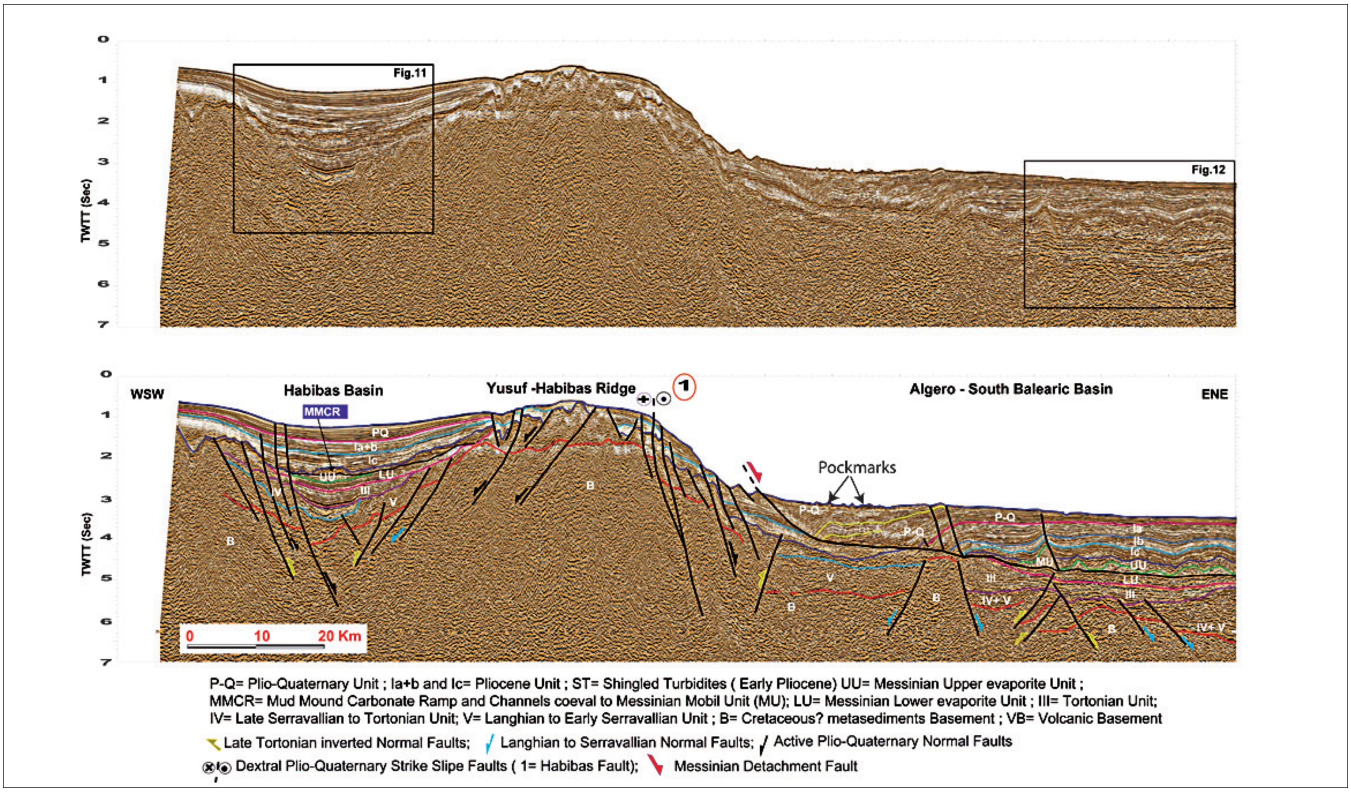


Figure 7. *Seismic cross section from the South Alboran Basin to the Algero-South Balearic Basin.*

organic content (TOC). Immediately offshore, in well Habibas-1, equivalent marls have up to 2% TOC and a hydrogen index over 400 with sapropelic kerogen assemblages. Older Miocene source rock levels not actually seen in the Habibas well are known more regionally. For example, in the Valencia Basin, offshore Spain, the Lower-to-Middle Alcanar marls are proven as a source rock (e.g., Cope et al., 2003).

The extensional regime of the crust and the relatively young age of the Miocene basins surrounding the Yusuf-Habibas Ridge suggest that present-day surface heat flow should still be relatively high, positively impacting the maturation of all possible source formations. Unfortunately, heat-flow data are not available for well HBB-1; however, ODP-975, south of the Balearic Islands, has recorded values of 81 mW/m². Several sites in the Alboran Basin have recorded values in excess of 100 mW/m² (e.g., Fernandez-Ibañez and Soto, 2008). Using these values and a simple rifting model, it can be demonstrated that potentially source-prone Miocene section would be currently in the oil window.

A geochemical study of well HBB-1 between 1550 and 4334 m showed that the majority of the measured TOC within the Miocene section is lower than 1% (actually, between 0.25 and 0.8%). 1D geochemical modeling (Figure 8) was performed using the IFP-EN Genex software to illustrate the hydrocarbon generation timing of three selected clay potential source-rock layers interpreted as transgressive shales: Serravallian clay at 3284–3308 m, corresponding to 12.7 Ma in age with TOC of 0.6–1.13%; Tortonian clay at 2770–2830 m, 9.26 Ma in age, with TOC of 0.8–0.9%; Messinian clay at 2387-2320 m 6.96 Ma in age, with TOC of 0.6%.

The modeling results show that only the Serravalian and Tortonian clay levels reached the oil window, at 2.5 Ma and 1 Ma, respectively. The Messinian clay level is still immature. The Habibas model shows that the best kitchen areas should be expected deeper than 2700 m. Therefore, in this region, the Langhian or Aquitanian and Burdigalian lacustrine source rocks deposited during the syn-rift period might be considered as effective source rocks as well.

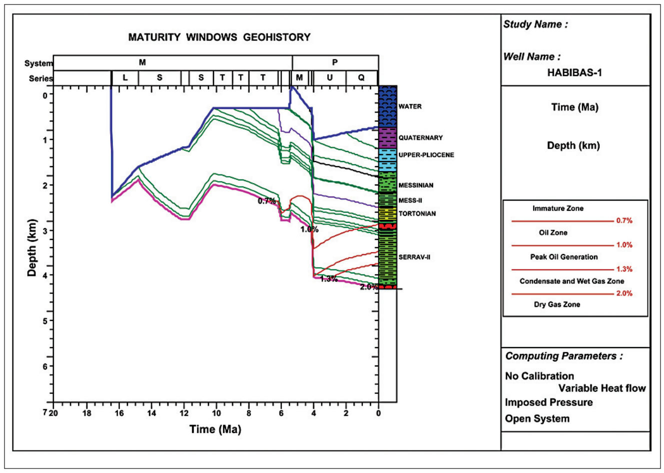


Figure 8. Burial and maturity history geological modeling of well Habibas-1.

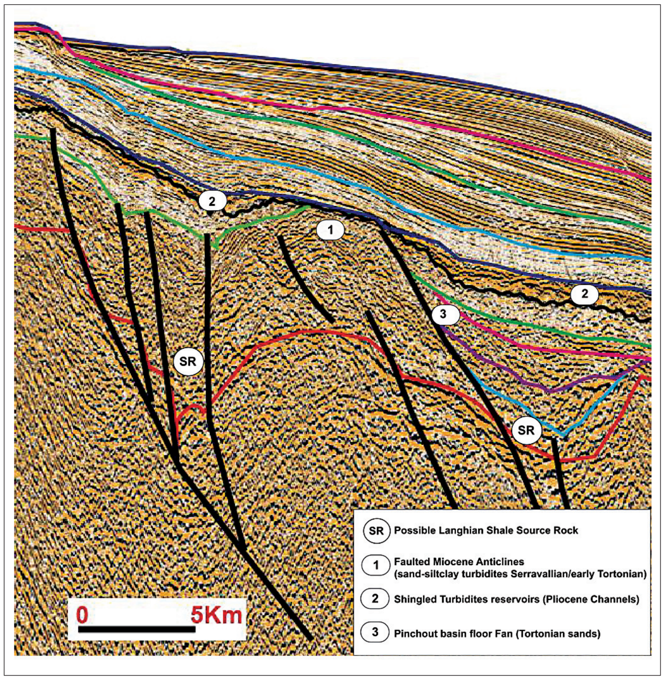


Figure 9. Miocene-to-Pliocene Habibas Basin petroleum plays related to faulted anticlines and transported upper Miocene sub-basin.

Petroleum plays and traps

Several petroleum plays are recognized in the surroundings of the Yusuf-Habibas Ridge which are closely related to the geological history of this transition domain.

South Alboran Basin. The Algerian margin forms a broad plateau with less than 1000 m water depth. The oil system would be favorable if there are source rocks present in syn-rift Miocene section (Burdigalian-to-Late Tortonian). In the Habibas Basin, the Early Miocene source rocks still unknown; the seismic sections (Figure 9) display only the Middle-to-Upper Miocene syn-rift strata.

The Habibas Basin sedimentary section has significant reservoirs at three main levels (Pliocene, Tortonian and Serravallian). These three sandstone levels encountered by well HBB-1 are interpreted to be associated with the erosion of the Pre-Miocene strata at the Yusuf-Habibas Ridge. This erosion would have supplied the Serravalian sandstones as basin floor fans, the late Tortonian and the Pliocene sands as shingled turbidites, and the Messinian sands as slope channels. A chaotic level visible in seismic data but not well described by the existing well data may represent a carbonate reservoir level at the base of the Pliocene (Figure 11).

There are two main trap types in the Habibas Basin: (a) structural traps, represented by Early Miocene anticlines and traps associated with tilted blocks and (b) stratigraphic traps, such as pinch-outs against tilted fault blocks, basin floor fan turbidites, mound carbonates, and Messinian paleo-valleys. The hydrocarbons potentially generated from the Langhian and Serravallian source rocks migrated vertically into the anticlinal traps and then laterally into the stratigraphic traps. The charge/trap timing is favorable because generation/expulsion has been modelled as post-Pliocene (2.5 Ma). The trap seals are provided by

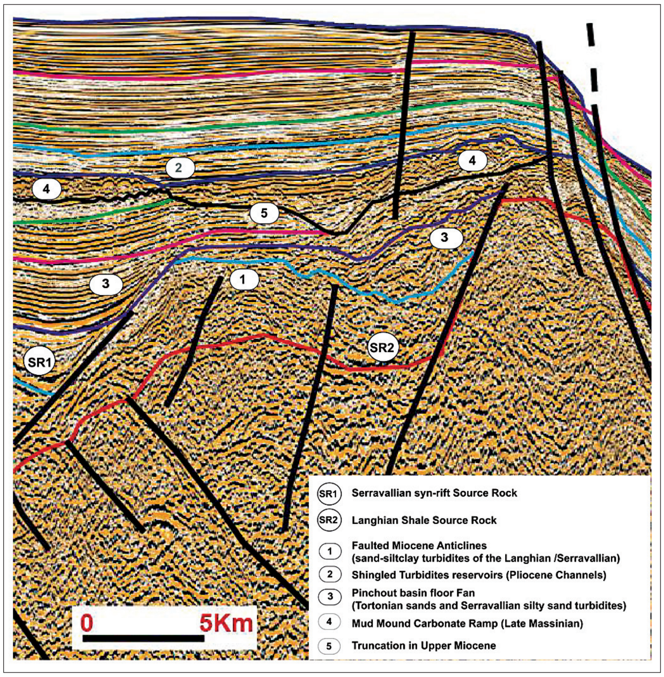


Figure 10. *Miocene-to-Pliocene Habibas Basin petroleum plays related to Early Miocene tilted blocks.*

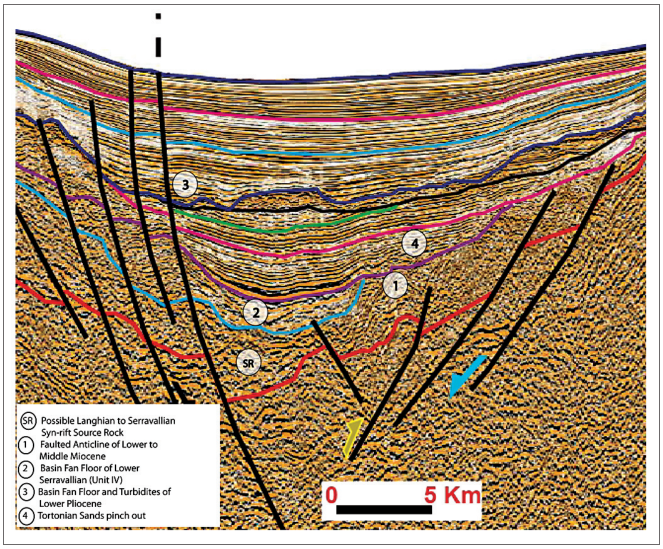


Figure 11. *Miocene-to-Pliocene pull-apart Habibas Basin and its petroleum plays and traps.*

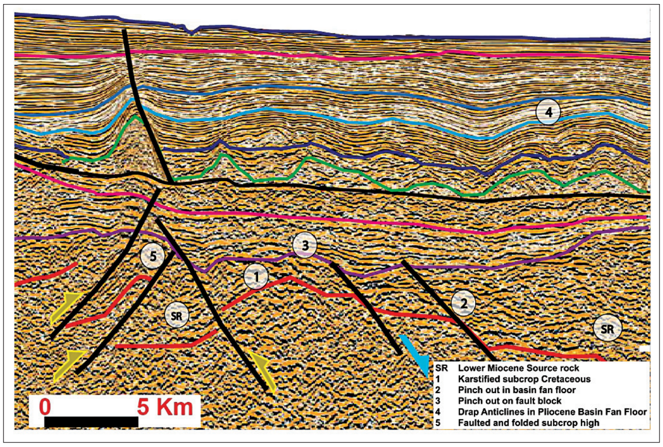


Figure 12. *Miocene-to-Pliocene Algero-South Balearic Basin petroleum plays related to Early Miocene tilted blocks and related inversion structures.*

the various clay layers interbedded between the reservoirs. The basin modeling done for well HBB-1 indicated effective Middle and Upper Miocene source rocks. However, the critical exploration risk within the Habibas Basin is related to the presence and effectiveness of source rocks.

South Algero-Balearic Basin. Eastward from the Yusuf-Habibas Ridge, the water is deep (2500 m). The interpretation of a WSW-ENE seismic cross section (Figure 7) suggests the presence of older Miocene syn-rift source rocks of possibly Burdigalian age. Between tilted syn-rift fault blocks the Middle Tortonian-to-Messinian series filled the depressions. The post-salt deposits are organized into folds, roll-overs and diapirs induced by detachment faulting on the salt. This tectonic decoupling defines two distinct petroleum systems:

Pre-salt petroleum system. Source rocks are assumed to be present in the Lower to Middle Miocene (Burdigalian?) syn-rift deposits. These source rocks have been documented in the onshore Cheliff Basin. There are multiple potential reservoir levels, within the Serravallian and Tortonian strata, equivalent to those of the onshore Ain Zeft Field of the onshore Chellif Basin. The traps are related to various tilted blocks and Tortonian-aged inversion structures. Stratigraphic traps associated with the pinchout of Tortonian-Messinian sediments are also considered as a viable play. The charge element of this petroleum system appears to be favorable as the Miocene source rocks are sufficiently buried beneath a thick Plio-Quaternary sequence.

Post-salt petroleum system. The source rock for this system is assumed to be Messinian-to-Middle Miocene in age. The reservoirs are Messinian carbonates and Pliocene basin floor fan or shingled turbidite sandstones. The traps could be anticlines, diapirs and roll-over structures, all related to detachment on the Messinian salt. Some of the anticlines show gas chimneys or pockmarks. The exploration risk in this case is related to Pliocene seal quality and charge/trap timing as the structures tend to be very young (i.e., Plio-Quaternary).

Conclusions

The Yusuf-Habibas Ridge is a continental fragment of the Alboran plate. Given its unique location at the plate boundary between Europe and Africa, the ridge recorded a long history of deformation between these plates. In particular, the north-south relative convergence of Africa and Europe during the Quaternary is marked by a dextral strike-slip along the Yusuf-Habibas Fault forming the Yusuf pull-apart basin.

A careful study of the available seismic sections tied to well HBB-1 clearly shows that the basement of the Yusuf-Habibas Ridge is mostly metamorphic sediments (whose age remains unclear) and Miocene volcanics. Above this substratum, seismic data depict only Pliocene-to-Quaternary deposits and NNW-SSE normal faulting which indicate a collapse toward both

Habibas and Algerian and South-Balearic basins. The polyphase structural evolution of the Yusuf-Habibas Ridge is summarized below:

- After the development of an Oligocene-Miocene magmatic arc in the Alboran block, the Yusuf-Habibas Ridge was formed during the Tortonian. The uplift of the ridge is linked with the collision of the Alboran plate to the Rif and Betic domains at ca. 10 Ma. The ENE-WSW Tortonian compressive phase, caused by the northeasterly motion of Africa relative to Europe at that time, led to the formation of NW-SE folds and marks the development of the Messinian piggy-back Habibas Basin.
- During the Messinian, evaporites accumulated in Habibas Basin—Unit II in Figure 4, equivalent of Lower Unit (LU) and Upper Unit (UU) in Figures 6 and 7. Well HBB-1 on the shelf (Figure 1) has not penetrated any Messinian salt deposits. The early Pliocene period is marked by the erosion of the existing ridges and seamounts and the overall sedimentation became progressively sandier.
- During the Pliocene and the Quaternary, the WNW-ESE faults bordering the Yusuf-Habibas Ridge were acting as dextral strike-slip structures. This strike-slip movement induced the opening of the Yusuf pull-apart basin and normal faulting on the flanks of the ridge. A detachment fault was associated with the Messinian salt—forming salt domes, diapirs, and rollover structures in the Plio-Quaternary deposits.
- The proper understanding of the polyphase deformational episodes in the broader Habibas Ridge and Basin appears to have an important impact on the exploration potential of this part of offshore Algeria. TLE

References

Alvarez-Marrón, J., 1999, Pliocene to Holocene structure of the eastern Alboran Sea (Western Mediterranean), in R. Zahn, M. C. Comas, and A. Klaus, eds., Proceedings of the Ocean Drilling Program, scientific results 161: Ocean Drilling Program, 345–355.

Booth-Rea, G., C. R. Ranero, J. M. Martinez-Martinez, and I. Grevemeyer, 2007, Crustal types and Tertiary tectonic evolution of the Alboran Sea, western Mediterranean: Geochemistry Geophysics Geosystems, **8**, no. 10, Q10005, http://dx.doi.org/10.1029/2007GC001639.

Bracene, R., A. Bellahcene, D. Bekkouche, E. Mercier, and D. Frizon de Lamotte, 1998, The thin-skinned style of the South Atlas Front in central Algeria, in D. S. Macgrefor, R. T. J. Moody and D. D. Clark-Lowes, eds, Petroleum geology of North Africa: Geological Society, London, Special Publication, **133**, 395–404.

Burollet, P. F., A. Said, and P. Trouve, 1978, Slim holes drilled on the Algerian shelf, in D. A. Ross and Y. P. Neprocnov, eds., Initial reports of deep sea drilling project: Government Press, 1181–1184.

Chalouan, A., R. Saji, A. Michard, and A. W. Bally, 1997, Neogene tectonic evolution of the southwestern Alboran Basin as inferred from seismic data off Morocco: AAPG Bulletin, **81**, 1161–1184.

Comas, M., V. García-Dueñas, and M. J. Jurado, 1992, Neogene tectonic evolution of the Alboran Sea from MCS data: Geo-Marine Letters, **12**, nos. 2–3, 157–164, http://dx.doi.org/10.1007/BF02084927.

Comas, M., A. Klaus, J. P. Platt, J. I. Soto, and A. B. Watts, 1999, The origin and tectonic history of the Alboran basin: insights from Leg 161 results, in R. Zahn, M. C. Comas, and A. Klaus, eds., Proceedings of the Ocean Drilling Program, scientific results 161: Ocean Drilling Program, 555–580.

Cope, M. J., 2003, Algerian licensing round may offer opportunity for exploration plays in deep offshore frontier: First Break, **21**, 35–40.

Fernández, J. R., R. Zahn, M. C. Comas, and A. Klaus, 1999, The sedimentary record of the Alboran basin: An attempt at sedimentary sequence correlation and subsidence analysis? Proceedings of the Ocean Drilling Program, scientific results 161: Ocean Drilling Program, 69–79.

Fernández-Ibáñez , F., and J. I. Soto, 2008, Crustal rheology and seismicity in the Gibraltar Arc (western Mediterranean): Tectonics, **27**, no. 2, TC2007, http://dx.doi.org/10.1029/2007TC002192.

Fernández-Ibáñez , F., J. I. Soto, M. D. Zoback, and J. Morales, 2007, Present-day stress field in the Gibraltar Arc (western Mediterranean): Journal of Geophysical Research, **112**, B8, B08404, http://dx.doi.org/10.1029/2006JB004683.

Jurado, M. J., and M. C. Comas, 1992, Well log interpretation and seismic character of the Cenozoic sequence in the Northern Alboran Sea: Geo-Marine Letters, **12**, nos. 2–3, 129–136, http://dx.doi.org/10.1007/BF02084923.

Martinez-Garcia, P., J. I. Soto, and M. Comas, 2011, Recent structures in the Alboran Ridge and Yusuf fault zones based on swath bathymetry and sub-bottom profiling: evidence of active tectonics: Geo-Marine Letters, **31**, no. 1, 19–36, http://dx.doi.org/10.1007/s00367-010-0212-0.

Mauffret, A., M. El-Robrini, M. Gennesseaux, 1987, Indice de la compression récente en mer Méditerranée: Un bassin losangique sur la marge nord-algérienne: Bulletin De La Societe Geologique De France, **3**, 1195–1206.

Mauffret, A., A. Maldonado, and A. C. Campillo, 1992, Tectonic framework of the eastern Alboran and western Algerian basins, western Mediterranean: Geo-Marine Letters, **12**, nos. 2–3, 104–110, http://dx.doi.org/10.1007/BF02084919.

Pérez-Belzuz, F., B. Alonso, and G. Ercilla, 1997, History of mud diapirism and trigger mechanisms in the Western Alboran Sea: Tectonophysics, **282**, nos. 1–4, 399–422, http://dx.doi.org/10.1016/S0040-1951(97)00226-6.

Platt, J. P., J. I. Soto, M. J. Whitehouse, A. J. Hurford, and S. P. Kelley, 1998, Thermal evolution, rate of exhumation, and tectonic significance of metamorphic rocks from the floor of the Alboran Extensional Basin, western Mediterranean: Tectonics, **17**, no. 5, 671–689, http://dx.doi.org/10.1029/98TC02204.

Ryan, W., K. J. Hsü, M. B. Cita, P. Dumitrica, J. Lort, W. Mayne, W. D. Nesteroff, G. Pautot, H. Stradner, and F .C. Wezel, 1973, Initial Report Deep Sea Drilling Project LIII: U.S. Government Printing Office.

Yelles-Chaouche, A. K., A. Boudiaf, H. Djellit, and R. Bracene, 2006, La tectonique active de la région nord-algérienne: Comptes Rendus Geoscience, **338**, nos. 1–2, 126–139, http://dx.doi.org/10.1016/j.crte.2005.11.002.

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